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Control Strategies Robust to Configurational Changes in Unmanned Underwater Vehicles

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a. Scientific/Technical Goals

This research addresses reliability and robustness issues in the control of unmanned underwater vehicles (UUVs) with focus on vehicles of interest to the Navy. The central goal is to study and develop the means for a UUV to compensate for both disruptive configurational changes such as the failure of an actuator as well as more gentle changes such as variations in vehicle parameters that may result, for example, from addition/release of equipment on-board, from motion or action of a robotic manipulator or simply from parameter uncertainty.

An important objective in support of the central goal is to use nonlinear methods to understand how to exploit nonlinear structure of UUV dynamics to advantage in control design. For example, it is often the case that one can show that a UUV is still controllable after an actuator failure. However, it is nonlinear methods that are required to verify this and it is nonlinearities in the UUV model that allow for the possibility of completing desired UUV motions after an actuator failure. Accordingly, it is nonlinear methods that should be used to develop algorithms that drive a UUV in the event of an actuator failure.

It is also an objective to systematize the generation of compensating control laws. For example, it is advantageous to have an algorithm that systematically generates control laws for a desired motion as a function of the given control authority, i.e., as a function of which actuators are available. Thus, in case an actuator becomes unavailable, the algorithm will automatically produce the amended control laws that require use of only the functioning actuators. In such a way one avoids a complicated and possibly time-consuming "case-by-case" strategy.

Another objective is to make use of advanced 3-D computer graphic capabilities to produce simulation tools that allow interactive, off-line visualization and testing of UUV dynamics and robust control strategies. These tools should be made modular to allow for flexibility, for example, in trying out different control strategies.

Finally, it is an objective to complement the above work with experimental studies on real vehicles.

b. Significant Accomplishments

Fin-Failure Compensation on Torpedo-Shaped UUVs

A major focus of the research has been on compensating for a stuck fin on torpedo-shaped UUVs of interest to the Navy, namely the 21UUV operated by NUWC, Newport Division. We have investigated the dynamics of the 21UUV especially with regard to fin failures and identified the critical issues associated with a stuck fin. Saturation of the remaining functional fins was identified as a critical issue. Accordingly, we have developed control laws that compensate for saturation and have demonstrated in simulation that the 21UUV can perform better in the event of a stuck fin using these laws.

The investigation into fin failures and control compensation is motivated by real failures that have occurred during in-water tests of the 21UUV. In particular, when power was lost to a fin's stepper motor, that fin got stuck at the deflection angle it was at at the time of power loss. As a result of the stuck fin, control of the vehicle was lost and the test was aborted. The compensation strategy we propose can be used to avoid having to abort tests and missions in the event of a stuck fin. While we focus on the 21UUV, our control design can be adapted to other torpedo-shaped UUV with one of four fins stuck.

In order to study the dynamics and control of the 21UUV, we use (a simplified version of) the nonlinear hydrodynamic model developed by Vehicle Control Technologies. We first compute equilibrium motions at various speeds and for various vehicle parameters (e.g., different net buoyant forces). These are computed under normal conditions and under various stuck fin conditions. Plots of the results illustrate the nature of the saturation problem as a function of the failure and operating conditions.

Our nominal controller is a sliding mode controller that is an improved version of the existing 21UUV controller. This controller can handle low speeds as well as some fin failures when used together with a modified fin mixing algorithm driven by information about the failure. In particular, we assume that the fin that is stuck and the angle it is stuck at are known by means of a failure identification package such as that described by Melvin (Masters Thesis, NPS, 1998).

As fin deflection saturation is a problem for the 21UUV even during normal operation (because of the negative angle-of-attack that is required to balance the net buoyant force on the vehicle), we augment the sliding mode controller design with a dynamic controller that is dedicated to compensating for saturation. This is an application of the theory developed by Teel and Kapoor (Proc. European Control Conference, 1997). This anti-windup controller, as it is called, is driven by the difference between the desired fin deflection and the actual deflection. If the fins are not saturated, this error signal is zero and only the sliding mode controller is active. However, when saturation occurs, the anti-windup controller turns on and drives the fins away from saturation without destroying the stability of the system. The

fact that the anti-windup controller is only active when there is saturation allows the nominal controller to be designed independently for desired performance under non-saturation conditions.

Our complete controller has been tested on the simulator for the 21UUV, a full-scale, 21-inch diameter, torpedo-shaped UUV. The results of these tests demonstrate good tolerance to a fin failure. As our objective is the design of failure compensation, we assume in our work that we have available an identification package that provides fin failure information. Our simulator test results suggest, however, that only very little information about the failure is required for effective compensation.

A 3D graphics simulation has been developed specifically to demonstrate our control strategies for compensating for a stuck fin on the 21UUV.

Compensation for Thruster Failures

Control algorithms have been designed for repositioning and reorienting a UUV near hover (i.e., close to zero velocity) that can adapt to actuator (thruster) failures. This is a flexible and general solution that allows one to exploit the nonlinearities in the system model to advantage. The control algorithms are derived systematically using tools from differential geometry, nonlinear control theory and mechanics. We have also explored the global phase space for the equations of motion of a rigid body in an ideal with the expectation that natural dynamics can be used to advantage, particularly in the event of a failure.

Development of Interactive 3-D Simulation

An interactive 3-D graphical simulation platform for UUV dynamics and control has been developed. The simulation package provides a platform on which we can test off-line how the control system will behave. The interactive feature allows the user to change system parameters during operation using the mouse. The control algorithms that adapt to actuator failures have been implemented on this platform. While the simulation is running, the user simply clicks the mouse to indicate that an actuator has failed and then watches how the control system copes with the failure. A special version of the software has been developed to test and demonstrate fin failure compensation on the 21UUV operated by NUWC Newport Division.

Robust Stabilization of UUVs

New results have been obtained for robust control of UUVs in steady motion. In this work we show how to stabilize steady motions of a UUV using physically motivated control laws. These control laws do not rely on cancellation of nonlinearities, but instead use the nonlinearities to advantage. Cancellation of nonlinearities may not be robust since hydrodynamic parameters are typically poorly known. Further, cancellation of nonlinearities may be inefficient. Our approach is robust to model parameter uncertainty because we exploit structure in the model rather than parameter values.

Further, sensor robustness comes about from our control laws. This is due to the fact that there is flexibility in our control laws as to which dynamic variables need to be measured and fed back. In particular, in certain cases, one needs a measurement of orientation OR a measurement of linear velocity. Thus, for example, if one were using the velocity measurement and the associated sensor failed, one could quickly switch to the control law alternative that only required attitude measurements.

These stabilization laws have been implemented on the 3-D simulation platform.

c. Publications

- **JOURNAL ARTICLES**

1. N.E. Leonard, "Stability of a Bottom-Heavy Underwater Vehicle", *Automatica*, Vol. 33, No. 3, March 1997, p.331-346.
2. N.E. Leonard and J.E. Marsden, "Stability and Drift of Underwater Vehicle Dynamics: Mechanical Systems with Rigid Motion Symmetry", *Physica D*, Vol. 105, June 1997, p. 130-162.
3. N.E. Leonard, "Stabilization of Underwater Vehicle Dynamics with Symmetry-Breaking Potentials", *Systems and Control Letters*, Vol. 32, October 1997, p. 35-42.
4. P. Holmes, J. Jenkins, N.E. Leonard, "Dynamics of the Kirchhoff Equations I: Coincident Centers of Gravity and Buoyancy", *Physica D*, Vol. 118, July 1998 p. 311-342.
5. F. Bullo, N.E. Leonard and A.D. Lewis, "Controllability and Motion Algorithms for Underactuated Lagrangian Systems on Lie Groups," *IEEE Transactions on Automatic Control*, to appear 1999.

- **PAPERS IN REFEREED CONFERENCE PROCEEDINGS**

1. N.E. Leonard, "Stabilization of Steady Motions of an Underwater Vehicle", *Proceedings of the 35th IEEE Conference on Decision and Control*, Kobe, Japan, December 11-13, 1996, p. 961-966.
2. F. Bullo and N.E. Leonard, "Motion Control for Underactuated Mechanical Systems on Lie Groups", *Proceedings of the European Control Conference*, Brussels, Belgium, July 1997.
3. A.M. Bloch, N.E. Leonard and J.E. Marsden, "Stabilization of Mechanical Systems Using Controlled Lagrangians", *Proceedings of the 36th IEEE Conference on Decision and Control*, San Diego, CA, December 1997, p. 2356-2361.
4. F. Bullo and N.E. Leonard, "Motion Primitives for Stabilization and Control of Underactuated Vehicles," *Proceedings of NOLCOS '98*, Enschede, The Netherlands, July 1998, p. 133-138 (Invited paper).

5. N.E. Leonard, "Mechanics and Nonlinear Control: Making Underwater Vehicles Ride and Glide," *Proceedings of NOLCOS '98*, Enschede, The Netherlands, July 1998, p. 1-6 (Invited plenary paper).
6. A.M. Bloch, N.E. Leonard and J.E. Marsden, "Matching and Stabilization by the Method Controlled Lagrangians", *Proceedings of the 37th IEEE Conference on Decision and Control*, Tampa, FL, December 1998, p. 1446-1451.
7. C.A. Woolsey and N.E. Leonard, "Underwater Vehicle Stabilization by Internal Rotors," *Proceedings of the American Control Conference*, San Diego, CA, June 1999, to appear.

- **PAPERS IN OTHER CONFERENCE PROCEEDINGS**

1. N.E. Leonard, "Stability and Stabilization of Underwater Vehicle Dynamics", *Proceedings of the 30th Annual Conference on Information Sciences and Systems*, Princeton University, March 1996, p. 771-775. (Invited paper).
2. N.E. Leonard, "Stabilization of Underwater Vehicle Dynamics: A Geometric Perspective", *Proceedings of the Sixth International Offshore and Polar Engineering Conference*, May 1996. (Invited paper).
3. N.E. Leonard, "Geometric Methods for Robust Stabilization of Autonomous Underwater Vehicles", *Proceedings of the Symposium on Autonomous Underwater Vehicle Technology*, IEEE Oceanic Engineering Society, Monterey, CA, June 1996, p. 470-476.
4. J. Graver, J. Liu, C. Woolsey and N.E. Leonard, "Design and Analysis of an Underwater Vehicle for Controlled Gliding", *Proceedings of the 32nd Annual Conference on Information Sciences and Systems*, Princeton University, March 1998.
5. N.E. Leonard and C.A. Woolsey, "Internal Actuation for Intelligent Underwater Vehicle Control", *Proceedings of the Tenth Yale Workshop on Adaptive and Learning Systems*, Yale University, June 1998, p. 295-300. (Invited paper).
6. S.-F. Cheng and N.E. Leonard, "Fin Failure Compensation for an Unmanned Underwater Vehicle," *11th International Symposium on Unmanned Untethered Submersible Technology*, to appear August 1999.

- **THESES**

1. C. Voelkel, "An Interactive, Three-Dimensional Graphical Simulation for Autonomous Underwater Vehicle Dynamics and Control", M.S.E. Thesis, Princeton University, 1997.
2. J. Jenkins, "Autonomous Underwater Vehicle Dynamics and Motion Tracking," M.S.E. Thesis, Princeton University, expected 1999.
3. S.-F. Cheng, "Fin Failure Compensation for an Unmanned Underwater Vehicle," M.S.E. Thesis, Princeton University, expected 1999.

d. Response to Navy Requirements

The following describes how the research described above responds to several Navy requirements:

- UUV Program Plan (updated Mar 95)
  Develop submarine launched and recovered UUVs for high priority Navy Missions.

  The research addresses reliable and robust control of UUVs. A particular focus is on torpedo-shaped UUVs such as would be used in submarine launch and recovery missions.

- S&T Needs For Undersea Weaponry (29 Sept. 94)
  Autonomous fault tolerant control is required. Improved hydrodynamic control in energetic environments is required.

  An important aspect of fault tolerance is compensating for an actuator failure such as addressed in this research.

- Long-term Mine Reconnaissance System (LMRS) COEA
  System sortie reliability required is 0.96.
  System sortie launch capability required is 0.92.

  Reliability can be improved with robust and fault tolerant control strategies such as those under development in this work.

- Offboard Sensor Working Group Report (Jan 96)
  Increased emphasis on miniaturization for 21 inch diameter UUVs.

  The focus on miniaturization precludes the use of redundant hardware or overdesigning subsystems to improve reliability. Improved reliability by means of control algorithms is sought. Thus, the work here on developing algorithms to systematically compensate for actuator failures helps address this need.

- Defense Technical Area Plan (April 96)
  A 10X increase in UUV reliability/robustness is the objective.

  A 10X increase in UUV reliability and robustness will require UUV control strategies that can compensate for both disruptive configurational changes such as the failure of an actuator as well as more gentle changes such as variations and uncertainty in vehicle parameters both of which are addressed in this research.

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13. ABSTRACT (Maximum 200 words)

This research addresses reliability and robustness issues in the control of unmanned underwater vehicles (UUVs) with focus on vehicles of interest to the Navy. The central goal is to study and develop the ability for a UUV to compensate by means of control for disruptive configurational changes such as the failure of an actuator. Several different aspects of the problem have been investigated. A major focus of the research has been on compensating for a stuck fin on torpedo-shaped UUVs of interest to the Navy, namely the 21UUV operated by NUWC, Newport Division. We have developed compensating control laws that address critical issues such as fin deflection saturation. Our controllers have been tested on our newly developed interactive 3D graphical simulation platform. Further, we have tested our algorithms on the simulator for the 21UUV at NUWC, Newport. The results of the tests show significantly improved tolerance to a fin failure.

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